

EVALUATION OF CDMA SYSTEM CAPACITY FOR MOBILE SATELLITE SYSTEM APPLICATIONS

MR. PATRICK O. SMITH, Communications Systems Engineer, TECHNO-SCIENCES, Inc., United States; DR. EVAGGELOS A. GERANIOTIS, Department of Electrical Engineering, University of Maryland, United States.

TECHNO-SCIENCES, Inc.
7833 Walker Drive, Suite 620
Greenbelt, MD 20770
United States

ABSTRACT

We discuss a specific Direct-Sequence/Pseudo-Noise (DS/PN) Code-Division Multiple-Access (CDMA) mobile satellite system (MSAT) architecture. We evaluate the performance of this system in terms of the maximum number of active MSAT subscribers that can be supported at a given uncoded bit-error probability. Our evaluation decouples the analysis of the multiple-access capability (i.e., the number of instantaneous user signals) from the analysis of the multiple-access multiplier effect allowed by the use of CDMA with burst-modem operation. We combine the results of these two analyses and present numerical results for scenarios of interest to the mobile satellite system community.

I. INTRODUCTION

The use of Direct-Sequence/Pseudo-Noise (DS/PN) Code-Division Multiple Access (CDMA) has significant technical advantages for mobile satellite system (MSAT) applications relative to the use of Demand-Assignment /Frequency-Division Multiple Access (DA/FDMA). CDMA offers an improved method of exploiting the statistical characteristics of user behavior. In this paper, we refer to this effect as the multiple-access multiplier effect. In addition, the use of DS/PN CDMA can mitigate the effects of multipath channel characteristics and provide interference rejection of intentional or unintentional interference sources.

In this paper, we outline a specific DS/PN CDMA MSAT communications system and provide a preliminary performance evaluation of the number of active users that can be supported at a given uncoded bit-error probability. The analysis of the multiple-access capability (i.e., the maximum number of instantaneous users for a given bit-error probability) is decoupled from the analysis of the multiple-access multiplier effect. The two analyses are combined to obtain preliminary estimates of the system capacity. More complete descriptions, analyses, and results can be found in [TECHNO-SCIENCES, 1988].

II. COMMUNICATIONS SYSTEM DESCRIPTION

A. MSAT System Overview

The MSAT system is intended to provide low data rate (i.e., less than 9.6 kbps) communications to a large number of geographically-dispersed low-duty-cycle mobile users. The MSAT system consists of a Network Management Center (NMC), multiple

hub/gateway stations, a single geosynchronous communications satellite, and the mobile users. The NMC grants access to the system, provides demand-assignment of available resources, and maintains appropriate network status and billing information. Hub/gateway stations provide connectivity to and from the Public Switched Telephone Network (PSTN). Base stations are similar to hub/gateway stations but are used by a specific subset of mobile users only.

B. Satellite Architecture / System Connectivity

Figure 1, Satellite Architecture / System Connectivity, shows the functional satellite architecture and system connectivity for the CDMA MSAT communications system analyzed in this paper. As shown, the satellite provides for "bent-pipe" frequency translation of mobile transmissions at L-Band to Ku-Band for reception at the NMC or hub/gateway stations. Similarly, Ku-band transmissions from the NMC or hub/gateway stations are frequency translated to L-Band for reception by the mobile receivers.

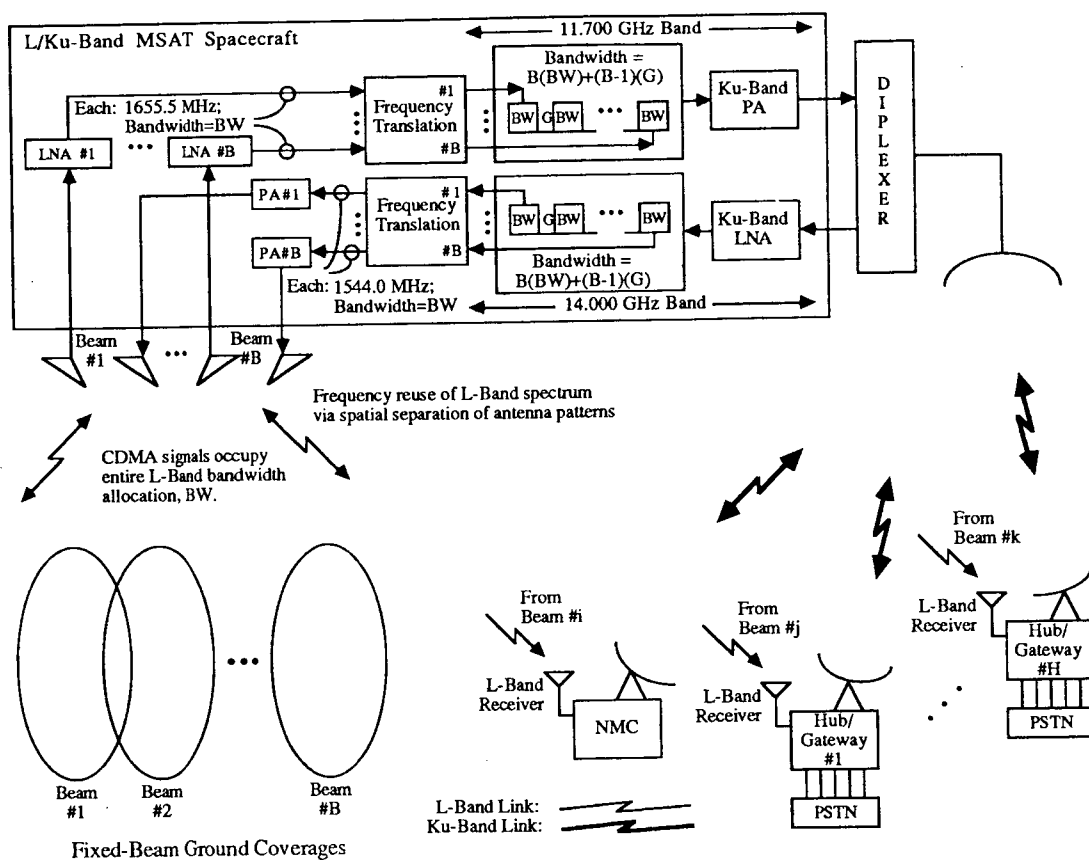


Figure 1. Satellite Architecture / System Connectivity

Frequency reuse of the L-Band spectrum is provided by spatial separation of B L-Band coverage beams. Figure 1 shows the use of fixed L-Band coverage beams. Each fixed L-Band coverage beam maps to a unique, nonoverlapping portion of Ku-Band spectrum. Thus, B-times frequency reuse of the L-Band spectrum corresponds to B-times frequency expansion of the Ku-Band spectrum.

An alternative to the use of fixed coverage beams is the use of electronically-steerable coverage beams. In this case, each of the B L-Band coverage beams would now span the entire coverage region. Signals received by each L-Band coverage beam are again downlinked at Ku-Band using a unique portion of Ku-Band spectrum. However,

in this case each NMC and/or hub/gateway station must appropriately align the relative phases of the B received beams to focus the effective antenna gain pattern at an optimal location. The effective antenna gain pattern can be focussed anywhere within the entire coverage region. Antenna patterns can be formed on a mobile-by-mobile basis by the use of independently operating beam-steering equipments. Explicit use of the CDMA signal characteristics of each mobile allow for the beam-steering capability without the need for geographical knowledge of the mobile location [Davisson and Flikkema].

C. DS/PN Codes and Phase Relationships

A broadcasted short DS/PN code provides system synchronization among all elements. This synchronization allows the use of a single DS/PN long code to provide simultaneous access of the channel by numerous users. Each user is allocated a unique phase epoch of the long code relative to system time at the NMC. The phase epochs are chosen and maintained so that overlap of different phase epochs cannot occur at any receiver. Figure 2, CDMA DS/PN Network Design, shows the DS/PN phase relationships for signals transmitted by the NMC.

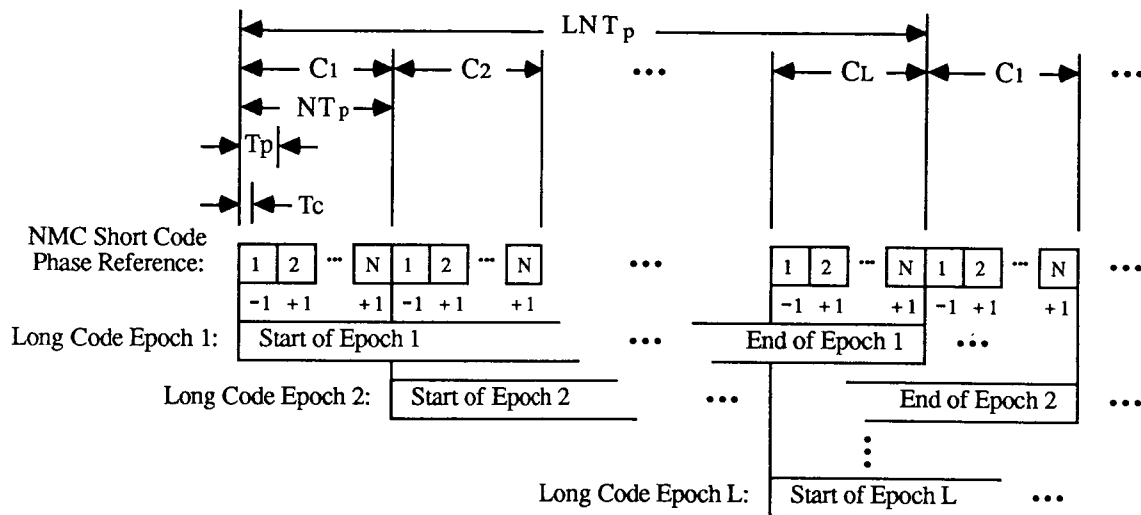


Figure 2. CDMA DS/PN Network Design

1. Short Codes. The NMC short code length, T_p , must be long enough to mitigate a given multipath delay spread and to provide favorable spectral content but short enough to allow reasonable DS/PN epoch acquisition times for mobiles entering or reentering the system. The mobile transmitters will use short codes of similar length to provide a random-access capability for circuit allocation requests. Several mobile transmitter short codes with good cross correlation properties can be used.

2. Long Code. Time shifted versions of a single long code are used to create a circuit allocation capability. Long code epochs are separated by N repetitions of the NMC short code epoch, where the first repetition of the NMC short code in each long code epoch is a complemented version of the NMC short code.

D. Mobile Transceiver Requirements

The use of an omni-azimuth mobile antenna pattern and DS/PN signal processing techniques provides for low-cost mobile transceivers in large quantities. The NMC short code must be acquired and continually tracked to provide an accurate time and frequency reference. Variable power control is required to optimize system capacity and minimize

shadowing effects for a given bit-error probability and availability. Burst-modem transmission and reception is required to achieve the resource-sharing multiplier effect allowed by CDMA. Burst operation simplicity and performance is considerably enhanced by the use of the NMC short code as a reference for the mobile.

III. EVALUATION OF SYSTEM CAPACITY

A. Single-Beam Analysis Considerations and Simplifying Assumptions

Our preliminary performance results are based on a number of simplifying assumptions, some of which are now stated. The results of this paper are valid for the fixed-beam MSAT spacecraft described in Section II B. We have assumed the simplified generic beam scenario as shown in Figure 3, which shows an arbitrary beam having two adjacent, partially overlapping beams. As shown there are two distinct coverage regions within the generic beam, namely, a center of beam region and an edge of beam region. The number of users in any given area is assumed to be proportional to the area. Now, the total number of active users that can be supported by the CDMA MSAT system will depend on the actual geographical location of the users and will be upper-bounded by Bk and lower-bounded by k for a given user location scenario. Here, B is the number of spacecraft transmit/receive L-Band beams required to span the entire coverage region and k is the number of active users supported by the generic beam.

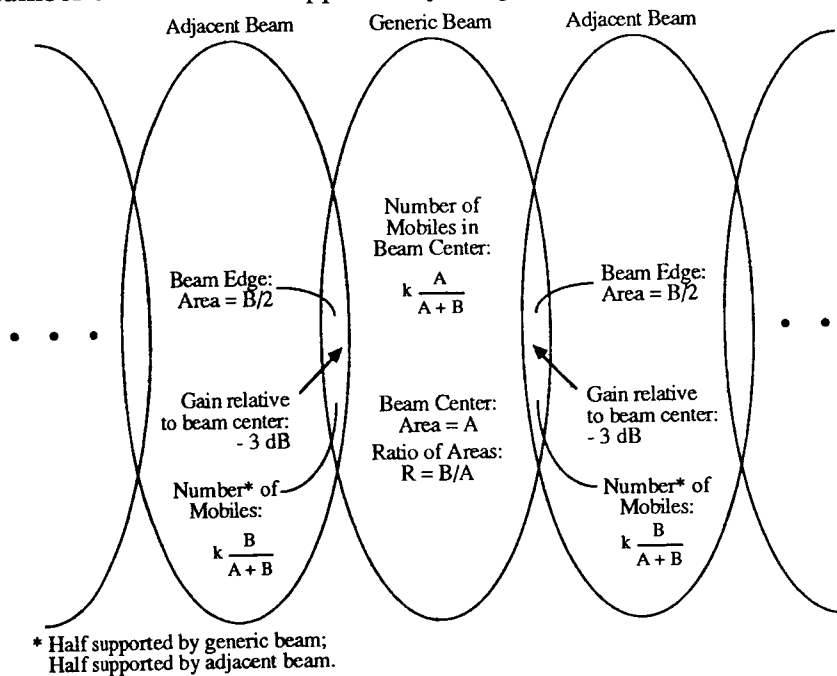


Figure 3. Simplified (Two Region) Beam-Coverage Scenario

We have assumed uncoded BPSK chip and data modulation over a Rician, frequency-selective channel with coherent demodulation. We have not restricted the available mobile terminal EIRP or spacecraft EIRP. In addition, we have assumed a simple power allocation scheme, which is based solely on user location relative to the two coverage regions of Figure 3, viz., mobiles in the edge of the beam area are allocated twice the power of mobiles in the center of the beam area.

For the hub-to-mobile direction we assume that the DS/CDMA signals are combined using pairs of orthogonal carriers with randomized chip delays. In the mobile-to-hub direction, it is not feasible for pairs of mobile transmitters to maintain orthogonal carriers.

B. Bit-Error Probability vs. Number of Instantaneous Subscribers (Hub-to-Mobile)

The reader is referred to the references for a more complete presentation of the subsequent results. Based on the previously stated assumptions and simplifications, the bit-error probability at time t , $\text{BEP}_{\text{center}}(k,t)$, at a mobile receiver in the center of a generic beam supporting k instantaneous users is given by:

$$\text{BEP}_{\text{center}}(k,t) = Q \left\{ \left[[2\alpha(t)\frac{E_b}{N_0}]^{-1} + \frac{\gamma^2}{3\eta} + \left(\frac{1+\gamma^2}{3\eta}\right)\left(\frac{1+4R}{1+2R}\right)k \right]^{-1/2} \right\} \quad (1a)$$

which approximates to:

$$\text{BEP}_{\text{center}}(k,t) \approx Q \left\{ \left[\frac{\gamma^2}{3\eta} + \left(\frac{1+\gamma^2}{3\eta}\right)\left(\frac{1+4R}{1+2R}\right)k \right]^{-1/2} \right\} \quad \text{for } 2\alpha(t)\frac{E_b}{N_0} \gg 1 \quad (1b)$$

where the notation is defined as follows:

- γ^2 = the power ratio of the reflected path to direct path of the Rician channel
- R = the ratio of the edge of beam area to the center of beam area
- η = the ratio of the data-bit modulation period to the chip modulation period
- $\alpha(t)$ = direct signal attenuation factor at time t

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-u^2/2} du$$

The relation for the bit-error probability, $\text{BEP}_{\text{edge}}(k,t)$, of a mobile receiver at the edge of a generic beam supporting k instantaneous users is identical to (1a) and (1b) except the factor $(1+4R)$ is replaced with $(1+6R)$. Thus, a more refined power allocation algorithm is desirable.

C. Multiple-Access Multiplier Factor

The question to be answered is the following. Given that a generic beam can support a total of k active users, how many users should be granted the resources of a circuit allocation? One rule would be to allocate the number, N , of users such that with a probability of say 0.95 the number of instantaneous users does not exceed the maximum that can be supported at a given bit-error probability. Here we describe a simple first-order statistical analysis to answer this question. For simplicity, we will assume the all-voice-traffic scenario with burst-modem operation, i.e., a mobile or hub DS/PN modulated signal is transmitted only during segments of conversation.

Let $\{X_i, Y_i\}$, $i = 1, 2, \dots, \infty$, represent the on/off process of a voice-activated modem, where X_i and Y_i represent the transmitter-on and transmitter-off durations, respectively, for the i th cycle of the process. The process $\{X_i, Y_i\}$, $i = 1, 2, \dots, \infty$, consists of a sequence of independent, identically distributed (i.i.d.) random variables. At a randomly selected time, the probability that the transmitter is on is $E\{X\}/[E\{X\} + E\{Y\}]$ [Karlin and Taylor, 1975]. If there are N active, simplex voice transmitters in the hub-to-mobile direction and each voice transmitter has a similar but independent i.i.d. process, then at stationarity the number of signals present at a randomly selected time instant is binomially distributed with parameters N and $E\{X\}/[E\{X\} + E\{Y\}]$.

Thus, for a given allocation of users, N , the distribution of the number of instantaneous users accessing the channel is given in terms of the average values of the transmitter-on and transmitter-off durations of the users. This simple first-order model can be generalized to any collection of transmitter processes that can be reasonably modelled as mutually independent i.i.d. processes.

D. Numerical Results

Figure 4, $BEP_{center}(k,t)$ vs. k , shows that a generic beam can support several hundred instantaneous users at an uncoded bit-error probability of 10^{-3} for $\eta = 3333$, 1666, and 833. These values of η correspond to an 8 MHz chip rate with a user data rate of 2.4, 4.8, and 9.6 kbps, respectively. Other parameters of Figure 4 are $\gamma^2 = 0.1$, $R = 1/4$, and $2\alpha(t)\frac{E_b}{N_0} \gg 1$. As shown in Table 1, Multiple-Access Multiplier Values, most of the achievable multiplier effect is obtained for values of k_{max} exceeding 50. Thus, the overall system capacity can be estimated at about 2.5B times k_{max} assuming the all-voice traffic scenario and a voice transmitter activity ratio of one third. The asymptotic multiplier effect is equal to $[E\{X\} + E\{Y\}]/E\{X\}$ for other data sources. In any case, the system capacity is roughly given by MBk_{max} for a given scenario.

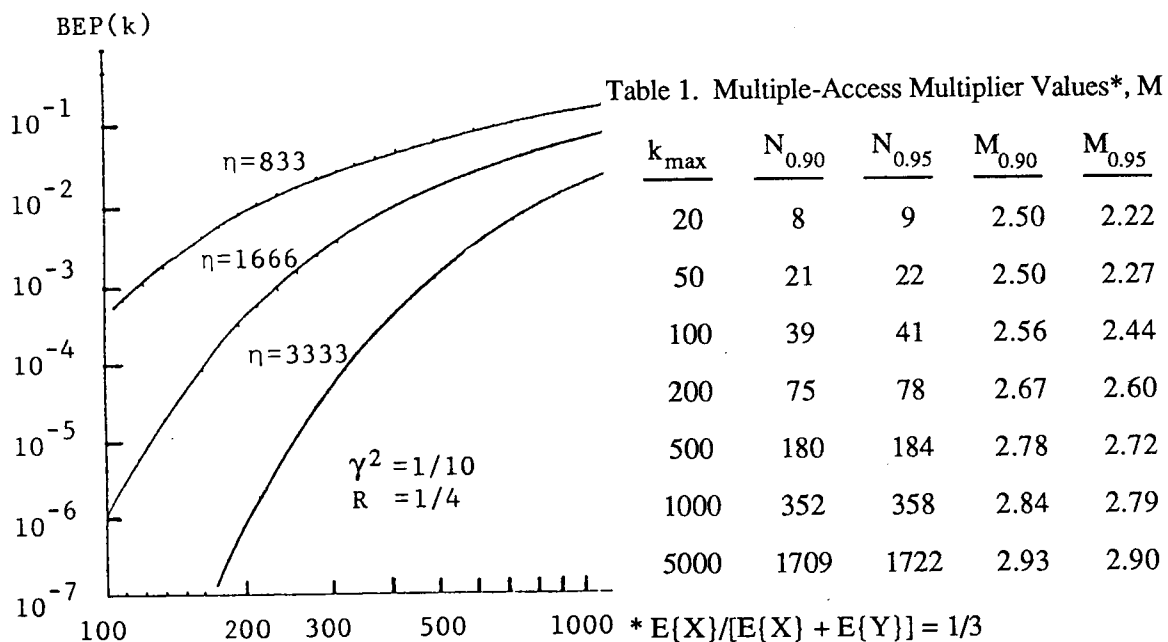


Figure 4. $BEP(k)$ vs. k

REFERENCES:

- Davisson, L. and Flikkema, P. Accepted for publication. "Fast Single-Element PN Acquisition for the TDRSS MA System," IEEE Trans. on Commun.
- Geraniotis, E. 1984. "Performance of Broadcast Direct-Sequence Spread-Spectrum Communications," in Proc. Conf. Inform. Sci. Syst., Princeton Univ., 1984.
- Karlin, S. and Taylor, H. 1975. A First Course in Stochastic Processes, Second Edition, Academic Press, 1975, pp. 201 and 202.
- TECHNO-SCIENCES, 1988. "Evaluation of CDMA System Capacity: SBIR Phase I Technical Report," to be submitted to NASA JPL.